

New Physics in $b \rightarrow s\bar{s}s$ Decay

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Abstract

We perform a model-independent analysis of the data on branching ratios and CP asymmetries of $B \rightarrow \phi K$ and $B \rightarrow \eta^{(\prime)} K^{(*)}$ modes. The present data is encouraging to look for indirect evidences of physics beyond the Standard Model. We investigate the parameter spaces for different possible Lorentz structures of the new physics four-Fermi interaction. It is shown that if one takes the data at 1σ confidence level, only one particular Lorentz structure is allowed. Possible consequences for the B_s system are also discussed.

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I Introduction

The data from B factories has reached a state where one can talk about looking for indirect signals of physics beyond the Standard Model (BSM) [1, 2]. Before the Large Hadron Collider (LHC) comes up, it seems we need a fare share of luck to directly produce BSM particles, be it of supersymmetry, technicolour, compactified extra dimensions, models with extra chiral/vector fermions, gauge bosons or scalars, or of some other extensions of the Standard Model (SM). On the other hand, radiative corrections induced by such new particles may affect low-energy observables.

The effects of specific models of BSM on low-energy data, particularly data from B factories, have been extensively discussed in the literature. Indeed, there is some justification for such an enthusiasm. It seems that the data is not exactly in harmony with the SM expectations. There are two caveats: the error bars are still large enough, and the low-energy dynamics is not very well known. The second point can be tackled by looking at the mixing-induced CP asymmetry data, where hadronic uncertainties mostly cancel out. Unfortunately, only for a limited number of channels such asymmetries have been measured. It is hoped that in near future we may have a situation where the error in the data will be dominated by theoretical uncertainties. We can only hope that the experimental numbers that we now have will stand the test of time and proceed accordingly.

If one looks carefully, the anomalous results seem to be concentrated in the $b \rightarrow s\bar{s}s$ decay sector. One can say that this is apparently so because we do not really understand the penguin dynamics, but the radiative decay $b \rightarrow s\gamma$ is well explained within the SM. This has prompted a number of analyses of the nonleptonic data, particularly those of $B \rightarrow \phi K$, in the context of specific new physics models, like different versions of supersymmetry [3], and non-supersymmetric models like extra Z' , more Higgs doublets, extra fermions, etc. [4]. A good guide about the anomaly is the Heavy Flavor Averaging Group (HFAG) website [1] (also the UTfit collaboration [2] performed some model-independent new physics analyses). The value of $\sin(2\beta)$, as extracted from all charmonium modes, is 0.725 ± 0.037 (this is consistent with the value obtained from CKM fits without superimposing the direct CP asymmetry measurement data), while it drops down to 0.43 ± 0.07 for $b \rightarrow s\bar{s}s$ modes. Both sets are internally consistent as far as exclusive modes are concerned. However, there is a second important factor: the branching ratios (BR) for $B \rightarrow \eta' K$ and $B \rightarrow \eta K^*$ channels are abnormally large, at

least if we do not take into account the *a posteriori* explanations of a large charm content of η or η' or the significant gluonic contributions. Some of the papers in [3] also deal with this BR enhancement problem. The data is shown in table 1.

Still, the results are not inconsistent with the SM. If we look at table 1, it is seen that $\sin(2\beta)$ extracted from $B \rightarrow \phi K_S$ is consistent with that extracted from the charmonium modes at less than 2σ . The BR data is never a clear indicator; *e.g.*, in the factorisation model [5] the $B \rightarrow \phi K$ BR is quite unstable with the variation of N_c , the effective number of colours, and one can always take help from SM dynamics beyond naive valence quark model to explain the BRs of $\eta^{(\prime)}$ modes. Only the value of $\sin(2\beta)$ from $B \rightarrow \eta' K$ is away from the charmonium value by almost 3σ . It is imperative to have more precise values of the CP asymmetries shown in table 1, and also accurate CP asymmetries from channels like $B \rightarrow 3K_S$ or $B \rightarrow K^+ K^- K_S$ [6].

Let us assume that the data, as it is, will stand the test of time. Even then this does not mean that only the $b \rightarrow s\bar{s}s$ channel is affected by BSM physics. Indeed, it will be very difficult to find a model which affects only one single channel. In particular, if at least two of the final state quarks are left-handed, then the SU(2) conjugate channel, $b \rightarrow c\bar{c}s$, will be there. The deciding factor is the SM contribution: for the former, it is a penguin contribution, whereas for the latter, it is a tree-level one, so the BSM amplitude has less chance to compete and show up in $b \rightarrow c\bar{c}s$ decays.

In this letter we perform a model-independent study of all $b \rightarrow s\bar{s}s$ channels that have shown signs of anomaly. There are a number of works in the literature [7, 8] that stress the need for such a model-independent analysis. We investigate what type of Lorentz structure of the four-Fermi interaction coming from the BSM physics can simultaneously solve all the anomalies. For simplicity, we do not include tensor currents, but all other bilinear covariants are taken into account. This serves as a testing ground for BSM models as far as their ability in explaining the anomalous B decay results are concerned. We will also assume that the new physics, whatever it is, does not contribute significantly to $B^0 - \bar{B}^0$ mixing; in particular, to the CP asymmetry prediction from the $B^0 - \bar{B}^0$ box diagram (*e.g.*, minimal supersymmetry with perfect alignment, *i.e.*, all flavour-changing δ parameters set to zero).

We will show that it is impossible to find a simultaneous solution for all BRs and CP asymmetries with a hierarchical structure of new physics (*i.e.*, only one Lorentz structure is numerically significant). The reason has been explained in section 3. We find that it is necessary to have some dynamics within SM but beyond the naive valence quark model (NVQM) to explain the BRs of the $\eta^{(\prime)}$ modes. Even with such an assumption, we have a fairly constrained parameter space, different for structurally different four-Fermi interactions, which can be further tested in hadronic machines (now that BTeV has been cancelled, this essentially means LHC-B).

Theoretically, a new Lorentz structure as discussed above should contribute to $B_s - \bar{B}_s$ mixing. This can potentially change the weak phase coming from the $B_s - \bar{B}_s$ box from the SM prediction of almost zero. This will directly affect the measured CP asymmetries in $B_s \rightarrow J/\psi\phi$, $B_s \rightarrow D_s^+ D_s^-$, $B_s \rightarrow \eta^{(\prime)} \eta^{(\prime)}$ channels. Unfortunately, the allowed parameter space for new physics can contribute only marginally in $B_s - \bar{B}_s$ mixing; the SM contribution, whose lower limit only exists, is too large. Thus, the effects can only be studied (hopefully) in a super-B factory, an e^+e^- collider sitting on the $\Upsilon(5S)$ resonance.

The first two decay channels, *i.e.*, $B_s \rightarrow J/\psi\phi$ and $B_s \rightarrow D_s^+ D_s^-$ will be further affected from BSM physics in decay if an SU(2) partner $b \rightarrow c\bar{c}s$ channel is present. However, we will show that this effect can be neglected. On the other hand, the channels $B_s \rightarrow \phi\phi$ or $B_s \rightarrow \eta^{(\prime)} \eta^{(\prime)}$, controlled by $b \rightarrow s\bar{s}s$ transition, should show modification from the SM prediction on two grounds: BSM physics in mixing as well as in decay. These predictions will be quantitatively different for different Lorentz structures.

II Data, Theory, and New Physics

The relevant data, after Moriond 2005, is taken from the HFAG website [1] (updated April 2005) and is shown in table 1.

| Final state | BR $\times 10^6$ | $\sin(2\beta)$ | A_{CP}^{dir} |
|----------------|------------------------|-----------------|-------------------------|
| ϕK_S | $8.3^{+1.2}_{-1.0}$ | 0.34 ± 0.20 | -0.04 ± 0.17 |
| ηK^{0*} | 18.7 ± 1.7 | | 0.01 ± 0.08 |
| $\eta' K_S$ | 68.6 ± 4.2 | 0.43 ± 0.11 | -0.04 ± 0.08 |
| $\eta' K^{0*}$ | < 7.6 | | |
| ηK_S | < 2.0 | | |
| ϕK^+ | $9.03^{+0.65}_{-0.63}$ | | -0.037 ± 0.050 |
| ηK^{+*} | $24.3^{+3.0}_{-2.9}$ | | $-0.03^{+0.10}_{-0.11}$ |
| $\eta' K^+$ | 70.8 ± 3.4 | | -0.027 ± 0.025 |
| $\eta' K^{+*}$ | < 14 | | |
| ηK^+ | 2.6 ± 0.5 | | 0.25 ± 0.14 |

Table 1: Experimental data on $b \rightarrow s\bar{s}s$ modes. For our convention of A_{CP} , see text. The third column shows the value of $\sin(2\beta)$ as extracted from mixing-induced CP asymmetry of the corresponding modes. The error bars are at 1σ confidence limit (CL); the upper limits are at 90% CL.

The theoretical numbers, particularly those for the BRs, have some inherent uncertainties that stem from low-energy QCD. We use the numbers from the conventional factorisation model with $N_c = 3$ [5, 9]. However, one may question the validity of such a simplified approach. Other models like QCD factorisation [10] or perturbative QCD [11, 12] differ in their predictions of the BRs for these modes. The reason for this difference is mainly twofold: first, the form factors for the factorizable diagrams are different, and second, the nonfactorizable topologies (like annihilation or emission) are given unequal importance in these models. A study shows that the predictions for the amplitudes vary at most by 20% (*i.e.*, more than 40% variation in the BRs) for the N_c -stable modes like $\eta(')K$, while ϕK modes are rather unstable and the amplitude uncertainty can go up to 40%. Since there is no consensus about which model one should use, we take the conventional factorisation numbers with an error margin of 20% in the amplitude level (and 40% for ϕK modes). This is just to take into account the variation of predictions for different models and should not be confused with the variation of a model parameter, say, N_c . The charm contribution in η or η' is neglected to start with, since that is an *a posteriori* approach to fix the BRs with the experiment. However, we will soon see that one must entertain either the possibility of a significant charm content in these mesons or a large gluonic contribution, *i.e.*, something beyond the NVQM, to satisfy the data even in the presence of new physics.

The CP asymmetries, particularly the mixing-induced ones that measure $\sin(2\beta)$, are more or less free from theoretical uncertainties. We assume that charm and up penguins are negligible compared to the top penguin, so that in the SM, $B \rightarrow \phi K_S$ is essentially a one-amplitude process. (Again, one can assume some phenomenological values for these penguins which reproduce the CP asymmetry data, thereby alleviating the need for any new physics.) The CP asymmetries are defined as

$$A_{CP} = \frac{\Gamma(B^+/B^0 \rightarrow f) - \Gamma(B^-/\bar{B}^0 \rightarrow \bar{f})}{\Gamma(B^+/B^0 \rightarrow f) + \Gamma(B^-/\bar{B}^0 \rightarrow \bar{f})}, \quad (1)$$

which differs in sign from the HFAG convention. More precisely, defining

$$\lambda = e^{-i\phi_M} \frac{\langle f | \bar{B}_d \rangle}{\langle f | B_d \rangle}, \quad (2)$$

where ϕ_M is the mixing phase ($\phi_M = 2\beta$ for $B^0 - \bar{B}^0$ mixing in the SM), we have

$$a_{CP}^d = \frac{1 - |\lambda|^2}{1 + |\lambda|^2}; \quad a_{CP}^m = \frac{2\text{Im}\lambda}{1 + |\lambda|^2}, \quad (3)$$

and the conventional S and $C(A)$ parameters are given by

$$S = -a_{CP}^m, \quad C = -A = a_{CP}^d. \quad (4)$$

For numerical analysis, we follow the values given in [5]; *e.g.*, the decay constants (in GeV) are

$$f_\pi = 0.133, \quad f_K = 0.158, \quad f_\phi = 0.233, \quad (5)$$

and we use $f_1 = 1.10f_\pi$, $f_8 = 1.34f_\pi$ with the one-angle mixing scheme (the two-angle one [13] makes little difference)

$$\begin{aligned} f_\eta^u &= \frac{f_8 \cos \theta}{\sqrt{6}} - \frac{f_1 \sin \theta}{\sqrt{3}}, & f_\eta^s &= -2 \frac{f_8 \cos \theta}{\sqrt{6}} - \frac{f_1 \sin \theta}{\sqrt{3}}, \\ f_{\eta'}^u &= \frac{f_8 \sin \theta}{\sqrt{6}} + \frac{f_1 \cos \theta}{\sqrt{3}}, & f_{\eta'}^s &= -2 \frac{f_8 \sin \theta}{\sqrt{6}} + \frac{f_1 \cos \theta}{\sqrt{3}}. \end{aligned} \quad (6)$$

Here $\theta = -22^\circ$, and $if_\eta^u p_\eta^\mu = \langle \eta | \bar{u} \gamma^\mu (1 - \gamma_5) u | 0 \rangle$, and similarly for other decay constants. The numerical values are $f_\eta^u = 0.099$, $f_\eta^s = -0.103$, $f_{\eta'}^u = 0.051$, $f_{\eta'}^s = 0.133$. Note that f_η^s and $f_{\eta'}^s$ are both large and of the same order of magnitude; this will be relevant for our future analysis.

The expressions for the SM amplitudes can be found in [5]. The regularisation scale is taken to be $\mu = m_b/2 \approx 2.5$ GeV and the quark masses according to [5] ($m_s = 0.5$ GeV, $m_u = m_d = 0.2$ GeV). We use the Wilson coefficients evaluated for $N_c = 3$ at next-to-leading order (NLO). Considering the fact that we have considered some inherent uncertainty in the amplitudes, it is expected that the results will be more or less stable with the variation of N_c . This is indeed found to be the case, but for more comments the reader is referred to the next section.

We discuss two different types of effective four-Fermi interactions coming from new physics:

$$\begin{aligned} 1. \text{ Scalar : } & \quad \mathcal{L}_{new} = h_s e^{i\phi_s} (\bar{s}_\alpha (c_1 + c_2 \gamma_5) s_\alpha) (\bar{s}_\beta (c_3 + c_4 \gamma_5) b_\beta), \\ 2. \text{ Vector : } & \quad \mathcal{L}_{new} = h_v e^{i\phi_v} (\bar{s}_\alpha \gamma^\mu (c_1 + c_2 \gamma_5) s_\alpha) (\bar{s}_\beta \gamma_\mu (c_3 + c_4 \gamma_5) b_\beta). \end{aligned} \quad (7)$$

Here α and β are colour indices. The couplings $h_{s,v}$ are effective couplings, of dimension $[M]^{-2}$, that one obtains by integrating out the new physics fields. They are assumed to be real and positive and the weak phase information is dumped in the quantities $\phi_{s,v}$, which can vary in the range $0-2\pi$. Note that they are effective couplings at the *weak* scale, which one may obtain by incorporating all RG effects to the high-scale values of them. The couplings c_1-c_4 can take any values between -1 and 1 ; to keep the discussion simple, we will discuss only four limiting cases:

$$\begin{aligned} (i) \quad (S+P) \times (S+P) [(V+A) \times (V+A)] & : \quad c_1 = 1, \quad c_2 = 1, \quad c_3 = 1, \quad c_4 = 1; \\ (ii) \quad (S+P) \times (S-P) [(V+A) \times (V-A)] & : \quad c_1 = 1, \quad c_2 = 1, \quad c_3 = 1, \quad c_4 = -1; \\ (iii) \quad (S-P) \times (S+P) [(V-A) \times (V+A)] & : \quad c_1 = 1, \quad c_2 = -1, \quad c_3 = 1, \quad c_4 = 1; \\ (iv) \quad (S-P) \times (S-P) [(V-A) \times (V-A)] & : \quad c_1 = 1, \quad c_2 = -1, \quad c_3 = 1, \quad c_4 = -1. \end{aligned} \quad (8)$$

This choice is preferred since the $1 - (+)\gamma_5$ projects out the weak doublet (singlet) quark field. For the doublet fields, to maintain gauge invariance, one must have an SU(2) partner interaction, *e.g.*, $\bar{s}(1 - \gamma_5)s$ must be accompanied by $\bar{c}(1 - \gamma_5)c$. No such argument holds for the singlet fields.

We have chosen the interaction in a singlet-singlet form under $SU(3)_c$. The reason is simple: one can always make a Fierz transformation to the local operator to get the octet-octet structure. Since no spin-2 mesons are involved, the transformations are particularly simple, as we can neglect the tensor terms.

The amplitudes for the various decay processes under consideration take the following form:

(i) $B \rightarrow \phi K$ (the contributions are same for neutral and charged channels):

$$\begin{aligned} i\mathcal{M}_s &= ih_s e^{i\phi_s} \left(-\frac{1}{2N_c} \right) \frac{1}{2} (c_1 c_3 - c_2 c_4) A_\phi, \\ i\mathcal{M}_v &= ih_v e^{i\phi_v} \left[c_1 c_3 \left(1 + \frac{1}{2N_c} \right) + \frac{1}{2N_c} c_2 c_4 \right] A_\phi, \end{aligned} \quad (9)$$

where

$$A_\phi = 2f_\phi m_\phi F_0^{B \rightarrow K}(m_\phi^2)(\epsilon_\phi \cdot p_B). \quad (10)$$

(ii) $B \rightarrow \eta^{(\prime)} K$ (again, since there is no $b \rightarrow s\bar{u}u$ new physics (NP) contribution, charged and neutral channels are equally affected):

$$\begin{aligned} i\mathcal{M}_s &= -ih_s e^{i\phi_s} \left[c_2 c_3 R(P, b, s) - \frac{1}{4N_c} \{ (c_2 c_3 - c_1 c_4) + (c_2 c_3 + c_1 c_4) R(P, b, s) \} \right] A_P, \\ i\mathcal{M}_v &= -ih_v e^{i\phi_v} \left[c_2 c_3 + \frac{1}{2N_c} ((c_2 c_3 + c_1 c_4) - (c_2 c_3 - c_1 c_4) R(P, b, s)) \right] A_P, \end{aligned} \quad (11)$$

where

$$R(P, b, s) = m_P^2 / 2m_s(m_b - m_s) \quad (12)$$

($P = \eta, \eta'$) is the chiral enhancement factor, and

$$A_P = if_P(m_B^2 - m_K^2)F_0(q^2), \quad q = p_B - p_K. \quad (13)$$

(iii) $B \rightarrow \eta^{(\prime)} K^*$: This follows a path similar to that discussed in (ii); however, only the axial-vector current contributes, and the expression for A_P looks slightly different:

$$A_P = 2m_{K^*} f_P (\epsilon^* \cdot p_B) A_0(q^2). \quad (14)$$

The chiral enhancement factor is given by $S(P, b, s) = -m_P^2 / 2m_s(m_b + m_s)$.

III Result

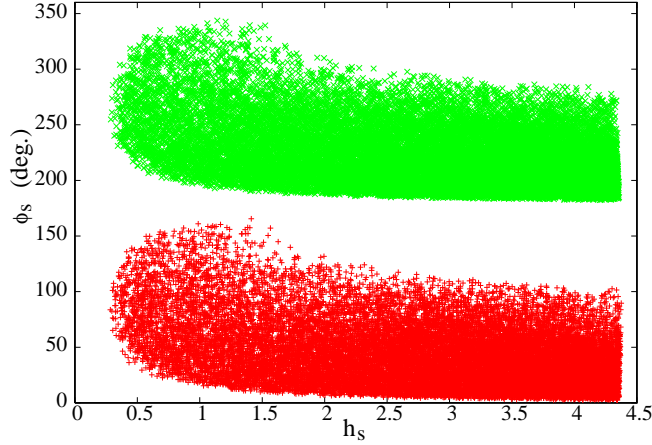


Figure 1: Allowed parameter space for $(S + P) \times (S + P)$ (lower red) and $(S - P) \times (S - P)$ (upper green) type new physics at 2σ confidence level. The NP amplitude is to be multiplied by 10^{-8} .

We are now ready to discuss our results. They are shown in figures 1-3 as the allowed parameter spaces for different Lorentz structures. The theoretical inputs have been summarised in the previous section, while the experimental inputs (BRs and CP asymmetries) are all listed in table 1. Note that since we are interested only in the $b \rightarrow s\bar{s}s$ transition, no other decay modes (like $B \rightarrow \pi\pi$ or $B \rightarrow \pi K$) have been taken into consideration. Although theoretically $b \rightarrow c\bar{c}s$ modes (like $B \rightarrow J/\psi K_S$) can be affected by the NP dynamics, the justification for not including them in the analysis (which essentially means neglecting the NP amplitude in the decay) comes *a posteriori* from the allowed amplitude of NP; this is so small compared to the tree-level Cabibbo-allowed SM amplitude that one can safely disregard them.

Apart from the BRs and CP asymmetries, we also use the following results from [1]:

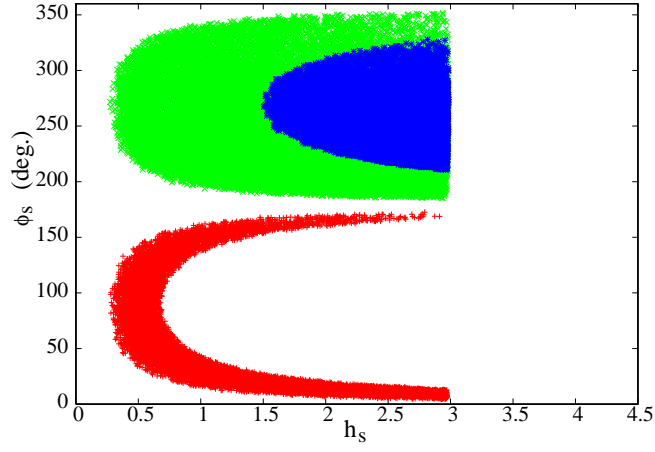


Figure 2: Allowed parameter space for $(S+P) \times (S-P)$ (lower red) and $(S-P) \times (S+P)$ (upper green) type new physics at 2σ confidence level. Also shown is the 1σ level parameter space (upper blue) for $(S-P) \times (S+P)$ type. The NP amplitude is to be multiplied by 10^{-8} .

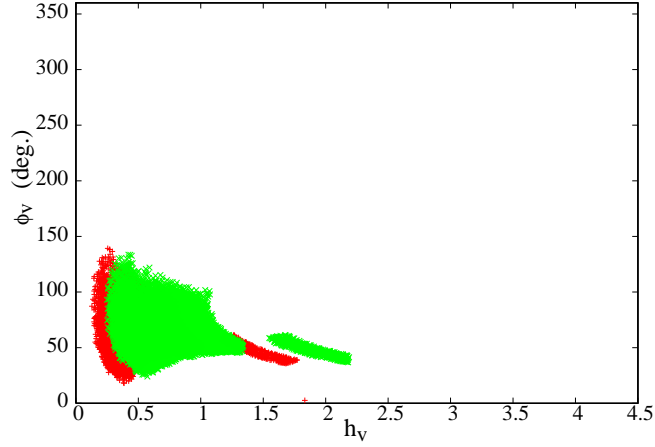


Figure 3: Allowed parameter space for $(V+A) \times (V+A)$ (red) and $(V+A) \times (V-A)$ (green) type new physics at 2σ confidence level. Note that at the bottom left corner, there is a large overlap between these two parameter spaces. The NP amplitude is to be multiplied by 10^{-8} .

- $\sin(2\beta)$ from charmonium modes: 0.725 ± 0.037 ;
- $\sin(2\beta)$ from the fit to the Unitarity Triangle plus ε_K [2]: 0.729 ± 0.042
- $\sin(2\beta)$ from $b \rightarrow s\bar{s}s$ transitions: 0.43 ± 0.07 ;
- $41^\circ < \gamma < 68^\circ$; dependence on γ , coming through the SM amplitudes of $B \rightarrow \eta^{(\prime)}$ modes, is completely negligible.

The magnitude of the CKM elements are taken from [14], with only the unitarity constraint imposed. All elements except V_{ub} and V_{td} are taken to be at their central values, while the full uncertainties for these two elements were incorporated. Again, due to the nature of the transition we are considering, this variation has almost no effect.

With the expressions for BRs and CP asymmetries at hand, we perform a scan on the new physics (NP) parameters $h_{s(v)}$ and $\phi_{s(v)}$. If we assume the NVQM to hold for the SM amplitude of $B \rightarrow \eta^{(\prime)}$, no common region is found that satisfy all the data. This leads us to relax the BR constraint on the $B \rightarrow \eta^{(\prime)}$ channels, *i.e.*, we assume that there is some SM dynamics beyond NVQM that generates a significant fraction of the amplitudes. We also assume that this dynamics does not affect the CP asymmetry predictions, *i.e.*, in the absence of NP, the mixing-induced CP asymmetry in $B \rightarrow \eta' K_S$ should give $\sin(2\beta)$ and the direct CP asymmetries in all these channels should vanish. The implementation of such a logic is performed by demanding that the contribution of the SM amplitude (NVQM part) plus that of the NP should not overshoot the experimental BRs (we find that the beyond-NVQM dynamics should generate 30-40% of the decay amplitudes for these modes).

Only the regions that satisfy all constraints are shown in figures 1-3. For the scalar-type new physics, it can be seen from figures 1 and 2 that all Lorentz structures are allowed when we take the experimental data at the 2σ confidence level (CL), and their ranges are also in the same ballpark, but what differs is the weak phase. This behaviour can easily be explained from the expressions of the NP amplitudes. Since we do not consider $SU(2)$ conjugate channels, there is no way to discriminate, as far as the magnitudes are concerned, between $SU(2)$ singlet and $SU(2)$ doublet type interactions. We have not taken into account any strong phase difference between the NP amplitude and that of the SM; since the direct CP asymmetries are compatible with zero for almost all channels (except $B \rightarrow \eta K$ by about 1σ) this is not such a drastic assumption. We have checked that if we switch the strong phase on, even the $B \rightarrow \eta K$ CP asymmetry data can easily be accommodated. However, strong phase differences cannot alleviate the necessity of introducing beyond-NVQM dynamics. If we take the experimental errors at 1σ instead of 2σ , only the $(S - P) \times (S + P)$ Lorentz structure remains allowed.

It is easy to understand why a simple NP model, without any contribution from beyond-NVQM dynamics, cannot explain the BR anomalies of the η and η' modes. If we take only a $b \rightarrow s\bar{s}s$ structure, the NP amplitude contributes equally to both $B \rightarrow \eta'$ and $B \rightarrow \eta$, the only difference being the factors f_η^s and $f_{\eta'}^s$, which happen to be numerically close. Thus, if the NP amplitude is taken to be so high as to jack up the $B \rightarrow \eta' K$ BR to the experimental value, it also raises the $B \rightarrow \eta K$ BR, which, however, is expected to be much smaller. The weak phase being fixed, we cannot even use the argument of constructive interference with the SM in one case and destructive interference in the other. Thus, one is forced to admit the possibility of some SM dynamics beyond NVQM to explain these decays.

For the vector channels, only two Lorentz structures are allowed: $(V + A) \times (V + A)$ and $(V + A) \times (V - A)$, both at 2σ . The structure $(V - A) \times (V + A)$ is a near miss; one can have a tiny overlap if the data (particularly the CP asymmetry data) shifts a bit. Thus, it is not entirely prudent to rule out such a structure right now. However, if the experimental error bars are taken at 1σ , all the allowed structures get ruled out. So, if the numbers remain as they are, and the error bars get smaller, there will be only one possible Lorentz structure of new physics. However, it is too early for such a prediction.

There are many well-motivated models that can generate such Lorentz structures. For example, minimal Supersymmetry can produce such vector-axial vector interactions, so does the model with extra gauge bosons in the left-right symmetric models. R-parity violating supersymmetry can produce tree-level scalar type interactions.

We have also checked the robustness of our results with the variation of the regularisation scale from $\mu = m_b/2$ to $\mu = m_b$, and found it to be minimal. This is not unexpected since at the NLO level the scale dependence of the Wilson coefficients becomes small. Finally, we have found that with the variation of N_c , some regions that are disallowed for $N_c = 3$ become allowed, but the result is more or less stable. For the scalar case, the results are absolutely N_c -stable (with a slight variation of the parameter space), when we vary N_c over the range 2 to 4. All structures are allowed at 2σ CL but only one, $(S - P) \times (S + P)$, at 1σ CL. For $N_c = \infty$, there are no allowed regions for any Lorentz structure, but that is only to be expected, since the $B \rightarrow \phi K$ NP amplitude vanishes at that limit.

For the vector case, with $N_c = 2$, the $(V + A) \times (V + A)$ and the $(V + A) \times (V - A)$ parameter spaces that we got for $N_c = 3$ remain almost unchanged. The other two structures now get allowed over a tiny parameter space, namely, $h_v < 0.4 \times 10^{-8}$ and $\pi < \phi_v < 2\pi$. The reason is that with the lowering of N_c , the c_2 -dependent term in eq. (9) becomes more important. These results are true for 2σ CL. Only the first two remain at 1σ CL, over the range $0.3 \times 10^{-8} < h_v < 1.1 \times 10^{-8}$, $20^\circ < \phi_v < 100^\circ$ (for $(V + A) \times (V + A)$), and $1.2 \times 10^{-8} < h_v < 1.6 \times 10^{-8}$, $28^\circ < \phi_v < 40^\circ$ (for $(V + A) \times (V - A)$). For $N_c = 4$ the results are almost identical with $N_c = 3$. The reason for this is essentially the highly unstable nature of the $B \rightarrow \phi K$ BR with the variation of N_c (remember that the variation of N_c is not the same as keeping $N_c = 3$ and taking different models of mesonic decays).

The result is stable with the variation of the other parameters (quark masses, form factors, CKM elements, etc.).

We have not discussed here the polarisation data of $B \rightarrow VV$ (*e.g.*, $B \rightarrow \phi K^*$) channels. This will be treated in detail in a subsequent publication [15]. We would just like to point out that a scalar-type new physics may significantly reduce the longitudinally polarised fraction in the decay $B \rightarrow \phi K^*$ [16] (for the experimental data see [1]).

IV Signatures in B_s System

We expect a large number of B_s decay channels to be probed in the hadronic machines. The first ones will include the gold-plated channel $B_s \rightarrow J/\psi \phi$ and $B_s \rightarrow D_s^+ D_s^-$, both occurring through the tree-level decay $b \rightarrow c \bar{c} s$. In the SM, the mixing-induced CP asymmetry is expected to be very small. It has been pointed out that new physics may introduce a nonzero CP asymmetry. There are two sources for that: (i) a new amplitude in the $B_s - \bar{B}_s$ mixing, with a nonzero weak phase, and (ii) a new contribution in the $b \rightarrow c \bar{c} s$ decay. It may so happen that both of them are present, and one needs a careful disentanglement of the two effects [17].

It can be shown that the new physics amplitude, given by $h_{s(v)}$, is at most 10% compared to the corresponding SM quantity for $b \rightarrow c \bar{c} s$ decay, namely, $(G_F/\sqrt{2})V_{cs}V_{cb}$. This, as far as the decay is concerned, NP effects will be extremely hard, if not outright impossible, to detect. This limits our discussion to NP effects in $B_s - \bar{B}_s$ mixing only. Note that this is not true if we consider final states like $\phi\phi$ or $\eta(\prime)\eta(\prime)$ that proceed through $b \rightarrow s \bar{s} s$ transition.

Unlike the decay, the calculation of the mixing amplitude depends on the precise structure of the NP Lagrangian, and one must perform a model-dependent study. Let us take the 1σ result, *i.e.*, the only possible Lorentz structure is $(S - P) \times (S + P)$. One of the prime candidates to generate such a structure is R-parity violating (RPV) supersymmetry, which leads to a slepton-mediated amplitude proportional to $\lambda'_{i22}\lambda'_{i23}^*$. It can easily be seen that

$$h_s = -\frac{\lambda'_{i22}\lambda'_{i23}^*}{4m_{\tilde{\nu}_i}^2}. \quad (15)$$

Thus, to be consistent with the decay data, the magnitude of the product of these two λ' s should be somewhere between 0.6×10^{-3} and 1.2×10^{-3} , and the associated weak phase between 0 and π (the minus sign takes care of a phase factor of $\exp(i\pi)$) for a sneutrino mass of 100 GeV. The necessary formalism to evaluate RPV contributions to the neutral meson mixing amplitude has been worked out in [18, 19]. Following these and

taking $\Delta M_s > 14.4 \text{ ps}^{-1}$ one can calculate the effective CP-violation in $B_s - \overline{B}_s$ mixing.

The result, however, is not really encouraging. The reason is simple: the SM amplitude is too large, enhanced from the $B^0 - \overline{B}^0$ mixing amplitude by at least a factor of $|V_{ts}|^2/|V_{td}|^2$ times ξ^2 , where $\xi = f_{B_s} \sqrt{B_{B_s}}/f_{B_d} \sqrt{B_{B_d}} = 1.21 \pm 0.06$ [20]. Furthermore, only a lower bound on the SM amplitude exists. The NP amplitude with such a weak coupling as obtained from the decay fit cannot compete with the SM amplitude. We find $\sin(2\beta_s)$, the effective phase from the $B_s - \overline{B}_s$ box, to be never greater than 0.1. Thus, it will be extremely unlikely to have a signal of this type of NP in $B_s \rightarrow J/\psi\phi$ decay. Note that for such a Lorentz structure, there will be a small but nonzero NP contribution to the $b \rightarrow c\bar{c}s$ decay.

One can, of course, integrate out the left-handed squark field and get the decay $B_s \rightarrow \ell_i^+ \ell_i^-$ (this is a strongly model-dependent statement and is true only in the context of RPV supersymmetry). For squarks at about 300 GeV, leptonic decay widths of B_s will be greatly enhanced; in particular $B_s \rightarrow \mu^+ \mu^-$ will be close to the experimental limit. (This set of couplings also enhances $B \rightarrow K^{(*)} \ell^+ \ell^-$ decay widths, but the constraints are more model-dependent.) Thus, these channels will be worth watching out.

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References

- [1] See <http://www.slac.stanford.edu/xorg/hfag/>, the website of the Heavy Flavor Averaging Group, for the winter 2004 update.
- [2] For CKM fits and predictions, see <http://utfit.roma1.infn.it> (the UTfit collaboration) and <http://ckmfitter.in2p3.fr> (the CKMfitter collaboration).
- [3] See, *e.g.*, D. Choudhury, B. Dutta, and A. Kundu, Phys. Lett. B456 (1999) 185; A. Datta, Phys. Rev. D 66 (2002) 071702; B. Dutta, C.S. Kim and S. Oh, Phys. Rev. Lett. 90 (2003) 011801; S. Khalil and E. Kou, Phys. Rev. D 67 (2003) 055009; A. Kundu and T. Mitra, Phys. Rev. D 67 (2003) 116005; S. Khalil and E. Kou, Phys. Rev. Lett. 91 (2003) 241602; G.L. Kane *et al.*, Phys. Rev. Lett. 90 (2003) 141803; M. Frank, Phys. Rev. D 68 (2003) 035011. K. Agashe and C.D. Carone, Phys. Rev. D 68 (2003) 035017; R. Arnowitt, B. Dutta, and B. Hu, Phys. Rev. D 68 (2003) 075008; B. Dutta *et al.*, Phys. Lett. B601 (2004) 144; Y. Wang, Phys. Rev. D 69 (2004) 054001; C. Dariescu *et al.*, Phys. Rev. D 69 (2004) 112003; P. Ball, S. Khalil, and E. Kou, Phys. Rev. D 69 (2004) 115011; J.-F. Cheng, C.-S. Huang, and X.-H. Wu, Nucl. Phys. B701 (2004) 54; Z. Xiao and W. Zou, Phys. Rev. D 70 (2004) 094008; Y.-B. Dai *et al.*, Phys. Rev. D 70 (2004) 116002; E. Gabrielli, K. Huitu, and S. Khalil, Nucl. Phys. B710 (2005) 139; M. Endo, S. Mishima, and M. Yamaguchi, Phys. Lett. B609 (2005) 95; S. Khalil, Mod. Phys. Lett. A19 (2004) 2745; D.T. Larson, H. Murayama, and G. Perez, hep-ph/0411178; P. Ko, J.-h. Park, and A. Masiero, hep-ph/0503102.
- [4] See, *e.g.*, A.K. Giri and R. Mohanta, Phys. Rev. D 68 (2003) 014020; C.-S. Huang and S.-h. Zhu, Phys. Rev. D 68 (2003) 114020; V. Barger *et al.*, Phys. Lett. B580 (2004) 186; N.G. Deshpande and D.K. Ghosh, Phys. Lett. B593 (2004) 135.
- [5] A. Ali, G. Kramer, and C.-D. Lü, Phys. Rev. D 58 (1998) 094009; Phys. Rev. D 59 (1999) 014005.
- [6] B. Aubert *et al.* (the BaBar Collaboration), hep-ex/0408076; K. Abe *et al.* (the Belle Collaboration), hep-ex/0409049; B. Aubert *et al.* (the BaBar Collaboration), hep-ex/0502019; K.F. Chen *et al.* (the Belle Collaboration), hep-ex/0504023;
- [7] D. London and A. Soni, Phys. Lett. B407 (1997) 61; D. Atwood and A. Soni, Phys. Rev. Lett. 79 (1997) 5206; B. Dutta and S. Oh, Phys. Rev. D 63 (2001) 054016; G. Hiller, Phys. Rev. D 66 (2002) 071502; C.-W. Chiang and J.L. Rosner, Phys. Rev. D 68 (2003) 014007; G.L. Kane *et al.*, hep-ph/0407351; G. Buchalla *et al.*, hep-ph/0503151.

- [8] T.E. Browder and A. Soni, hep-ph/0410192 (published in the *Proceedings of WHEPP-8*, ed. S. Uma Sankar and U.A. Yajnik, *Pramana* **63**, 1171 (2004)).
- [9] M. Wirbel, B. Stech, and M. Bauer, *Zeit. Phys. C* 29 (1985) 637; M. Bauer, B. Stech, and M. Wirbel, *Zeit. Phys. C* 34 (1987) 103.
- [10] M. Beneke *et al.*, *Phys. Rev. Lett.* 83 (1999) 1914; *Nucl. Phys.* B591 (2000) 313; M. Beneke *et al.*, *Nucl. Phys.* B606 (2001) 245.
- [11] Y.-Y. Keum, H.-n. Li, and A.I. Sanda, *Phys. Lett.* B504 (2001) 6; *Phys. Rev. D* 63 (2001) 054008; hep-ph/0201103; Y.-Y. Keum and H.-n. Li, *Phys. Rev. D* 63 (2001) 074006; C-D. Lu, K. Ukai, and M.Z. Yang, *Phys. Rev. D* 63 (2001) 074009.
- [12] Y.-Y. Keum and A.I. Sanda, *Phys. Rev. D* 67 (2003) 054009.
- [13] T. Feldmann and P. Kroll, *Eur. Phys. J. C* 5 (1998) 327; R. Escribano and J.-M. Frère, hep-ph/0501072.
- [14] S. Eidelman *et al.*, (Particle Data Group Collaboration), *Phys. Lett.* B592 (2004) 1.
- [15] S. Nandi and A. Kundu, in preparation.
- [16] P.K. Das and K.C. Yang, *Phys. Rev. D* 71 (2005) 094002.
- [17] G. Bhattacharyya, A. Datta, and A. Kundu, *J. Phys. G* 30 (2004) 1947.
- [18] G. Bhattacharyya and A. Raychaudhuri, *Phys. Rev. D* 57 (1998) 3837.
- [19] A. Kundu and J.P. Saha, *Phys. Rev. D* 70 (2004) 096002.
- [20] J. Charles *et al.* (the CKMfitter group), hep-ph/0406184.